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Electrodialysis reversal desalination: monographs for the design parameters

Maung Thein Myint[a,*], Abbas Ghassemi[a,b]

[a]*Institute for Energy and the Environment, New Mexico State University, MSC WERC, P.O. Box 30001, Las Cruces, NM 88003, USA*
Tel. +1 575 646 2073; Fax: +1 575 646 5474; email: mmyint@nmsu.edu
[b]*Chemical Engineering Department, New Mexico State University, MSC ChE, P.O. Box 30001, Las Cruces, NM 88003, USA*

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ABSTRACT

Electrodialysis reversal (EDR) is known for its excellence to desalt Ca^{2+} and SO_4^{2-} dominated brackish groundwater with a higher water recovery rate, an elevated silt density index (SDI 6-12), potential for biofouling, hard-to-treat, high hardness, and lower salinity feed waters with the ranges of 200–5000 mg/L TDS. The power index is the only currently available design and evaluating parameter for the EDR process; however, power index is only valid for the same total dissolved solid (TDS) concentrations of feed and product water. Since, ED/EDR is capable of treating a variable source of water quality while producing a consistent finished water quality, comprehensive design and evaluating parameters are required, identified and proposed in this study. The quantities of the design parameters were developed from 52 sets of literature experimental data that have 10 different types of feed water characteristics. Another one set of literature experimental data was used to validate the values of developed parameters. The data were analyzed and presented in the monographs depending on water recovery rate, dilute flow rate per effective area of membrane, and TDS concentration in the feed. The monograph reveals the amount of TDS removed (and volume of product water produced) rate over 1 m^2 of effective area of membrane from every unit of direct current, voltage, and power supplied to the membrane stack are 0–1.5 eq_{rem}/(h m^2e A); 0–0.06 eq_{rem}/(h m^2e V); and 0.1–1.4 (eq_{rem} $m^3{}_p$)/(h m^2e kWh) for the equal flow rate of EDR in 40–130 L/(h m^2e) of dilute flow rate per unit area of membrane, 53–90% of water recovery rate, and 1700–7190 mg/L of TDS in the feed. These values are found to be 3–3.9 eq_{rem}/(h m^2e A); 0.015–0.023 eq_{rem}/(h m^2e V); 0.1–0.35 (eq_{rem} $m^3{}_p$)/(h m^2e kWh) for 3–9 L/(h m^2e) of dilute flow rate and 2120–4260 mg/L of TDS in the feed water of unequal (dilute/concentrate = 3) flow rates of EDRs.

Keywords: Desalted current; Power; Voltage; Flow rate per effective area of membrane; Power index; TDS concentration in feed; Effective area of membrane

1. Introduction

In electrodialysis reversal (EDR) desalination, direct current is used to attract the ions from the feed dilute stream into the concentrate stream through the migration of ion-exchange membranes. Cations are permeated through the cation-exchange membrane, and anions are permeated through the anion-exchange membrane. By doing this, ions in the dilute stream deplete and ions in the concentrate stream increase from feed along the length of the flow paths of the respective stream. The product water is collected at the end of the dilute stream

*Corresponding author.

where ion concentrations are the least. In the classical EDR, flow rate, velocity, pressure in both dilute and concentrate streams are more or less the same [1] to prevent membrane bulging [2,3]. To gain a higher water recovery rate, WRR (WRR > 0.5), a fraction of wastewater from the effluent of the concentrate stream is required to recycle back into the inlet of the feed stream [4,5]. Power consumption per unit volume of water product (kWh/m^3) may change when EDR is operated with the higher WRR although in the same total dissolved solid (TDS) concentrations in the feed and product streams, and the same degree of product flow rate, due to the TDS concentration in concentrate increases [6], and the concentrate make-up and waste flow rates decrease.

The effectiveness of the EDR operation depends on the electro-chemical characteristics of feed water [7,8]; membrane characteristics; the dilute water flow rate [6,9–11]; voltage application rate [8,12], percentage of demineralization, water recovery rate [1]; mean-ion-residence-time of concentrate [3]; ionic species [13]; and ion concentration in concentrate stream [14]. The design parameters of EDR have to include the controlling parameters from the above factors to represent the most real conditions.

However, current design parameters available from literature are not included in all of the above controlling factors. For example, the voltage application rates in ED varies with 1–2 V/cell pair [15]; more exactly, the optimal potential of 1.15 and 1 V/cell pair are required for waters with TDS concentration of 0–24,170 and 27,100–36,000 mg/L in the feed of dilute stream, respectively [8]. The maximum voltage and current density application rates are below 2 V/cell pair and less than 250 A/m^2, respectively to prevent local overheating and chemical damage [16]; however, Lee [14] recommends the voltage application rate should be corresponding to the 80–90% of limiting current density (LCD). Ref. [2] specifically instructs the design current density should be 70% of LCD which is varied with TDS concentration in the feed of dilute stream. The design current density should vary with the feed TDS concentration in the feed of dilute stream. Typical water production rates in brackish water ED systems are about 20–25 gallons per sqft per day [15]. There exists a theoretical minimum of energy – of the order of one kilowatt-hour – for the production of one metric ton of fresh water from ocean water, but the practical processes use much more energy [12]. The current densities application rates in the desalting of brackish water containing 5000 ppm TDS generally lie between 6 and 20 mA/cm^2 (5.1–18.6 A/ft^2); the lifetime of membranes, however, decreases with the increasing of the current density. As desalting proceeds, the resistance rises and both current and salt shifting rates decrease until a new batch of raw feed water is processed [12]. To reduce the *capital* costs up front, engineers tend to design a capacity at a lower end but operate ED/EDR at a higher end of voltages, after the system was built, of the order of 1 V/cell pair, although *this entails a loss of electric power because the faster motion of the ions causes relatively more conversion of energy into heat* [12]; this practice may increase unnecessary power consumption and damage the membrane subsequently that add to the operational cost. The parameter of 1 V/cell pair may have to update with the energy per volume of product water, effective area of membrane, flow rate, TDS removed, and dominated ions. There is not enough information to pre-design the ED/EDR by using the above parameters.

Spiegler [12] developed a power index in Eq. (1) by the standardization of the water production rate in the unit membrane area to assess the desalted power consumption of units with different production sizes of desalination plants; Spiegler [12] also warned that the power index equation is only valid for the same inlet and product TDS concentrations due to the power consumption variation with the different inlet and product concentrations although in the same 1000 mg/L of TDS concentration removed.

$$\text{Power index} = \left(P_d / V_p\right) / \left(Q_p / Ame\right)$$
$$\text{Power index} = P_d Ame / \left(V_p Q_p\right) \tag{1}$$
$$\text{Unit inpower index} = \text{kWh h m}^2\text{e} / \left(\text{m}_\text{p}^6\right)$$

where P_d = power used in reduce TDS concentration in dilute stream, kW; (P_d does not include the power for pumping water); V_p = volume of product water, m^3; Q_p = product water flow rate, m^3/h; Ame = effective area of membrane, m^{2}e where e represents effective.

Since the power index is not recommended for the different inlet and product concentrations of water and does not contain current and voltage inputs, the objectives of this article are to develop monographs containing a set of comprehensive pre-design parameters that may have the ability to pre-design and evaluate an ED/EDR in the different concentrations of feed water.

2. Method

2.1. Proposed parameters

Three parameters that have units in eq$_\text{rem}$/(h m^{2}e A); eq$_\text{rem}$/(h m^{2}e V); eq$_\text{rem}$ m^3_p/(h m^{2}e kWh) are proposed here: The quantities of these parameters are developed based on the experimental data from the literature of EDR along with their inlet and product TDS concentrations and effective area of membrane used. Since TDS removed (eq$_\text{rem}$/h) is defined as the product water

Table 1
Design of experiments

Test	Flow per effective area of membrane, L/h m²e	% of ions of TDS in feed water Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	F^{-}	Feed TDS mg/L	# of cell p	Type	References
1	23.8, 16.7, 13.3, 8.3	32.8	0.0	4.2	0.0	50.0	12.8	0.0	0.28	2120	15	Interpolymeric	[7]
2	24.2, 18.3, 14.2, 10.0, 7.1	33.0	0.0	4.1	0.0	50.0	12.5	0.0	0.45	2120	15	films based on	[7]
3	23.3, 17.5, 11.3, 8.3, 6.7	33.3	0.0	4.0	0.0	50.0	12.1	0.0	0.71	2120	15	HDPE & LLDPE	[7]
4	20.8, 16.3, 11.3, 8.3, 5.8	33.6	0.0	3.8	0.0	50.0	11.7	0.0	0.94	2120	15		[7]
5	17.5, 15.0, 9.2, 6.7	34.1	0.0	3.3	0.0	52.3	10.1	0.0	0.17	3020	15		[7]
6	17.5, 13.3, 9.2, 6.7	34.3	0.0	3.2	0.0	52.3	9.8	0.0	0.33	3020	15		[7]
7	17.5, 14.2, 9.2, 7.5, 4.2	34.5	0.0	3.1	0.0	52.3	9.6	0.0	0.46	3020	15	Interpolymeric	[7]
8	19.2, 15.4, 10.8, 7.9, 4.6	34.7	0.0	3.0	0.0	52.3	9.3	0.0	0.66	3020	15	films based on	[7]
9	16.7, 11.8, 10.8, 6.7, 3.8	35.5	0.0	2.5	0.0	54.5	7.5	0.0	0.12	4260	15	HDPE & LLDPE	[7]
10	13.3, 10.8, 8.3, 6.7, 3.3	35.6	0.0	2.4	0.0	54.5	7.3	0.0	0.23	4260	15		[7]
11	15.0, 12.9, 9.2, 5.8, 4.6	35.7	0.0	2.3	0.0	54.5	7.1	0.0	0.35	4260	15		[7]
12	15.0, 11.7, 7.5, 5.0	35.9	0.0	2.3	0.0	54.5	6.9	0.0	0.47	4260	15		[7]
13	15.0, 12.1, 9.6, 7.1, 4.6	35.8	0.0	2.2	0.0	55.0	6.9	0.0	0.10	4800	15	Interpolymeric	[7]
14	15.8, 11.7, 8.3, 6.3, 4.6	35.9	0.0	2.2	0.0	55.0	6.7	0.0	0.19	4800	15	films based on	[7]
15	14.6, 11.3, 9.2, 6.7, 5.0	36.0	0.0	2.1	0.0	55.0	6.5	0.0	0.31	4800	15	ionics	[7]
16	15.0, 11.3, 9.2, 6.3, 4.6	36.2	0.0	2.1	0.0	55.0	6.3	0.0	0.42	4800	15	aquamite I	[7]
17	30.7	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	with cation-	[11]
18	44.3	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	CR67-HMR-	[11]
19	58.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	412 & anion-204-	[11]
20	71.6	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	SXZL- 386;	[11]
21	85.2	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	2 electric stage,	[11]
22	98.9	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	3 hydraulic stage	[11]
23	112.5	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100	per electric st.	[11]
24	126.1	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	3330	100		[11]
25	30.7	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
26	44.3	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
27	58.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
28	71.6	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
29	85.2	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
30	98.9	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
31	112.5	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
32	126.1	39.3	0.0	0.0	0.0	60.7	0.0	0.0	0.0	7190	100		[11]
33	94.6	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4060	450		[9]
34	92.2	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4190	450	CR61CZL	[9]
35	93.4	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4015	450	386 and	[9]
36	89.6	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4141	450	aromatic	[9]
37	92.4	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4010	450	103 PZL.	[9]
38	89.9	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4130	450		[9]
39	94.6	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	3965	450		[9]

(Continued)

Table 1 *(Continued)*

Test	Flow per effective area of membrane, L/h m^{2}e	% of ions of TDS in feed water Na$^+$	K$^+$	Ca^{2+}	Mg^{2+}	Cl$^-$	HCO_3^-	SO_4^{2-}	F$^-$	Feed TDS mg/L	# of cell p	Type	References
40	92.8	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4011	450	CR61CZL 386	[9]
41	92.4	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	3955	450	and aliphatic	[9]
42	92.8	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4069	450	204 SXZL.	[9]
43	91.0	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4023	450	Mark III-4	[9]
44	93.8	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4173	450	spacer	[9]
45	97.0	32.5	0.12	3.7	1.0	51.2	1.6	9.9	0.0	4056	450		[9]
46	95.9	14.6	0.00	12.4	3.9	27.7	12.7	28.7	0.0	1712	450	AR204 SXZL &	[6]
47	95.2	14.0	0.00	12.3	3.9	25.3	15.8	28.6	0.0	1693	450	CR61-CXL-386.	[6]
48	96.6	11.9	0.00	14.0	3.9	23.4	12.8	34.0	0.0	1806	450		[6]
49	96.6	12.7	0.00	13.7	4.0	23.8	12.8	33.0	0.0	1754	450		[6]
50	93.1	12.2	0.00	13.6	4.3	24.1	12.9	32.8	0.0	1848	450		[6]
51	94.1	12.7	0.00	13.5	4.1	26.4	12.1	31.1	0.0	1812	450	Mark III-4	[6]
52	93.1	15.0	0.00	12.0	3.7	27.7	12.9	27.3	0.0	1699	450	spacer.	[6]
53	78.2	13.5	0.0	9.0	4.2	2.1	30.9	40.2	0	1773	257	Aquamite V	[16]

m^{2}e = effective area of membrane, m^2 where e represents effective.

production rate (m^3_p/h) times the difference in TDS concentrations between inlet and effluent of dilute stream; the production rate is standardized in the third-parameter as in the power index. Moreover, the first- and second-parameters contain current and voltage information; the voltage and current application rates can be designed from these proposed parameters.

We did not conduct the experiments here, and we did only the analysis based only on the literature data. Fifty-two different lab experiments from literature were referred to and carried out for these works to calculate the values of the parameters with seven different feed waters, two different types of membranes, and more than 60 different flow rates per effective area of membrane. Another one set of literature lab data were used to validate the calculated values of the parameters. The details of the experiments are summarized in Table 1 which involves two types of ED/EDR – unequal and equal flow rates in dilute and concentrate streams.

2.2. Unequal flow rate in dilute and concentrate streams

Tests 1–16 were referred from experiment of [7]; the tests were operated with unequal flow rates between dilute and concentrate streams with the ratio of dilute to concentrate of 3. In the tests 1–16, an ED stack consisting of 15 cell pairs with cation- and anion-exchange membranes that are fabricated from interpolymeric films based on high-density polyethylene–linear low-density polyethylene–styrene–divinylbenzene [7] were used. After attaining a steady current, the unit was operated continuously for 6 h. Then electricity polarity was reversed, and the stack was run for another 1 h to prevent any scale formation from the hardness of brackish water.

2.3.Equal flow rate in dilute and concentrate streams

Tests 17–32 were referred from experiment of [11]. In test numbers 17–32, an "Ionics Aquamite I" EDR stack containing 100 cell pairs with the cation- and anion-exchange CATION-CR67-HMR-412 and ANION-204-SXZL-386 were used [11]. A stack was designed in two electrical stages with three hydraulic stages within each electrical stage using a Mark I spacer with 1 mm thickness and 348 cm flow path. Flow rates in cell pairs were 2–7 cm/s; current density application rates were 2–9 mA/cm^2 in electrical stage I and 2–5 mA/cm^2 in electrical stage II. The polarity reversal interval cycle was 15 min.

Data for tests 33–45 were referred from experiment of [9]. An Ionics Aquamite X EDR unit was used in test numbers 33–45 to desalt a high sodium chloride feed water that has an average TDS concentration of 4064 mg/L. A stack containing 450 cell pairs (457 × 1160 mm^2) in two electrical stages with three hydraulic stages each was used. The tests used in this data analysis were considered as two categories: the first category is from tests 33 to 39 where aromatic 204 SXZL anion membranes were used, the second category is from tests 40 to 45 where the aliphatic 103 PZL anion membranes were used. The same types of CR 61 CZL-386 cation-membrane and Ionics' Mark III-4 spacers were used in both categories with the same characteristics of feed water [9]. Test numbers 33–39 and 41–44 were operated with 20 min polar reversal intervals and test numbers 40 and 45 were with polar reversal intervals of 30 min. The detailed information can be found in [9].

Data for tests 46–52 were referred from experiment of [6]. A membrane stack consisting of 450 cell pair in three electrical and six hydraulic stages were used in test numbers 46–52. Ionics' Mark III-4 spacers, CR 61 CZL-386 cation membranes, and mainly 204 SXZL aliphatic anion membranes were used to desalinate a high sulphate containing feed water (TDS 1800 mg/L approximately). The 36 cell pairs of other anion membranes are interleaved in test sections in the first and last hydraulic stages. These test sections were made up of five cell pairs each of 204 RXZL, developmental 304 RXZL and 304 SXZL, and three cell pairs of 103 PZL anion membranes [6]. The test numbers 46–52 were operated without acid and antiscalant in the concentrate stream. The detailed information can be found in [6].

Tests 1–16 and 17–52 were used to develop the values of the parameters; test 53 was used to validate the calculated value. The data of test 53 was referred from [17].

3. Results and discussion

3.1. Unequal flow rate in dilute and concentrate streams

Experimental data for the test numbers 1–16 were shown in detail in [7] and summarized in here, Figs. 1–4 and Table 2. Each figure contains four types of subfigures (a)–(d). Based on their measured data, TDS removed (and volume of product water produced) rate over the effective area of membrane and power versus with TDS removed rate over the effective area of membrane and current were analyzed and shown in (a) of Figs. 1–4. The

Table 2
Resulting design parameters for ED/EDR: unequal flow rates between dilute and concentrate streams with a ratio of dilute and concentrate flow rate is 3/1

		Characteristics of water									Design parameters		
		% ions concentration in feed water						Product water			TDS removed rate over effective area of membrane and current	TDS removed rate over membrane area and voltage	TDS removed & product water produced rates over power, membrane area,
Test	Flow per unit area membrane L/(h m²e)	Na^+ %	Ca^{2+} %	Mg^{2+} %	Cl^- %	HCO_3^- %	F^- %	TDS mg/L	F^- mg/L	TDS mg/L	eq_{rem}/ (A m²e h)	$eq_{rem/}$ (h m²e V)	eq_{rem} m^3_p/ (kWh m²e h)
1	8.3	32.8	4.2	0.0	50.0	12.8	0.28	2120	1.5	420	3.858	0.019	0.309
2	7.1	33.0	4.1	0.0	50.0	12.5	0.45	2120	1.0	350	3.671	0.016	0.250
3	6.7	33.3	4.1	0.0	50.0	12.1	0.71	2120	1.0	338	3.555	0.016	0.228
4	6.6	33.6	3.8	0.0	50.0	11.7	0.94	2120	1.1	318	4.100	0.016	0.220
6	6.7	34.3	3.2	0.0	52.3	9.8	0.33	3020	1.5	480	3.734	0.022	0.239
7	4.4	34.5	3.1	0.0	52.3	9.6	0.46	3020	1.1	318	3.055	0.016	1.025
8	4.6	34.7	3.0	0.0	52.3	9.3	0.66	3020	1.0	358	3.170	0.016	0.139
9	3.8	35.5	2.5	0.0	54.5	7.5	0.1	4260	1.0	450	3.373	0.019	0.121
10	3.3	35.6	2.4	0.0	54.5	7.3	0.2	4260	1.0	430	3.328	0.017	0.106

Ratio of flow rates between dilute to concentrate streams = 3.

eq_{rem}/(h m²e A) = TDS removed rate over the effective area of membrane and current where eq represents equivalent weight of ions (TDS), and e represents effective.

eq_{rem}/(h m²e V) = TDS removed rate over the effective area of membrane and voltage where eq represents equivalent weight of ions (TDS), and e represents effective.

eq_{rem} m^3_p/(h m²e kWh) = TDS removed and product water produced rates over the effective area of membrane and power where eq represents equivalent weight of ions (TDS).
e represents effective, and p represents product water

relationship between TDS removed rate over the effective area of membrane and voltage versus TDS removed rate over the effective area of membrane and current are depicted in (b) of Figs. 1–4. Part figure (c) of Figs. 1–4 shows the TDS concentration in the product against TDS removed rate over the effective area of membrane and current. Part figure (d) of Figs. 1–4 shows the relation of F^- concentration in the product water against TDS removed rate over the effective area of membrane and current. Figs. 1–4 were tested with the initial feed TDS concentrations of 2120, 3020, 4260, and 4800 mg/L.

The average TDS concentrations in the product are fixed as 383 mg/L with the lowest and highest values of 318 and 480 mg/L depending on data availability for test numbers 1–16; the exact values used in the tests are shown in Column 14 of Table 2. By using the corresponding TDS concentration in the product, from the part figure (c) of Figs. 1–4, the corresponding values of TDS removed rate over the effective area of membrane and current are read from the TDS concentrations in the product stream. The resultant value of TDS removed rate over the effective area of membrane area and current is used to read the F^- concentration of product in part figure (d) of Figs. 1–4. The read-out F^- concentration has to be equal or less than 1.5 mg/L. If not, the TDS removed rate over the effective area of membrane and current is corrected with the value results from F^- concentration in feed from part figure (d) of Figs. 1–4. The corrected value of TDS removed rate over the effective area of membrane and current is used to determine the TDS removed (and volume of product water produced) rate over the effective area of membrane area and voltage (power) from part figure (b) (Fig. (a)) of Figs.

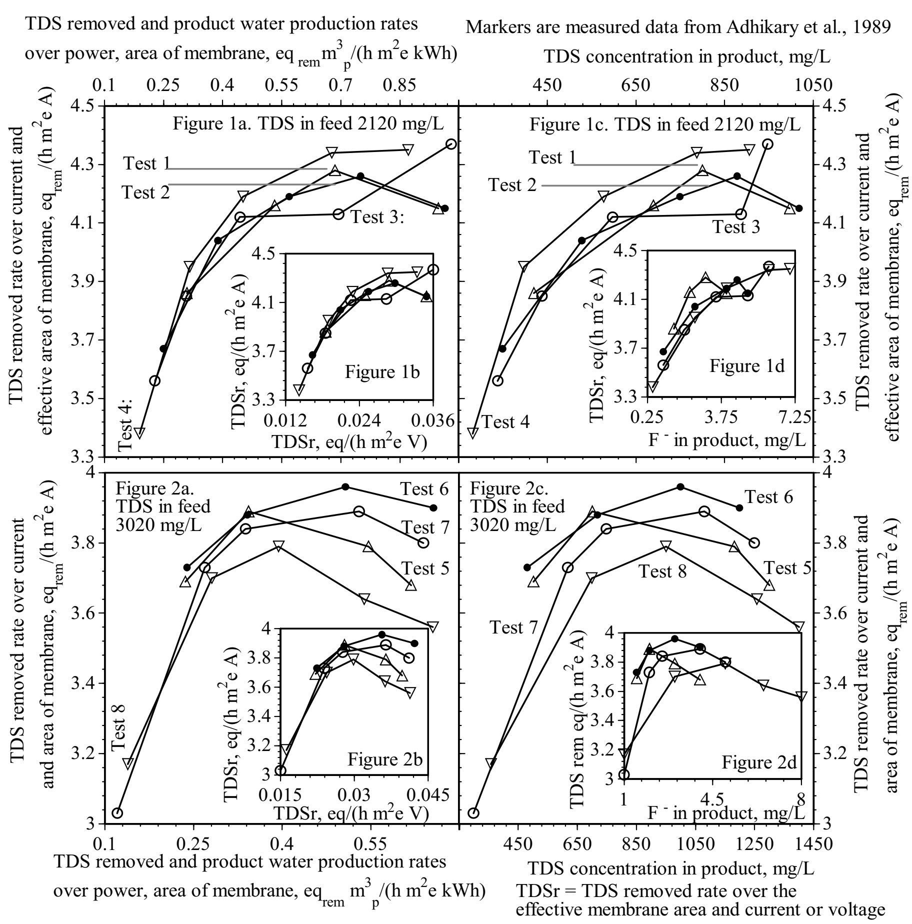


Fig. 1. Analyzed results for tests 1 to 4 with feed TDS 2120 mg/L.

Fig. 2. Analyzed results for tests 5–8 with feed TDS 3020 mg/L. (a) TDS removed and product water produced rates over the effective membrane area and power vs. TDS removed rate over the effective membrane area (EMA) and current. (b) TDS removed rate over EMA and voltage vs. TDS removed rate over EMA and current. (c) TDS concentration in product vs. TDS removed rate over EMA and current. (d) F^- concentration in product vs. TDS removed rate over EMA and current.

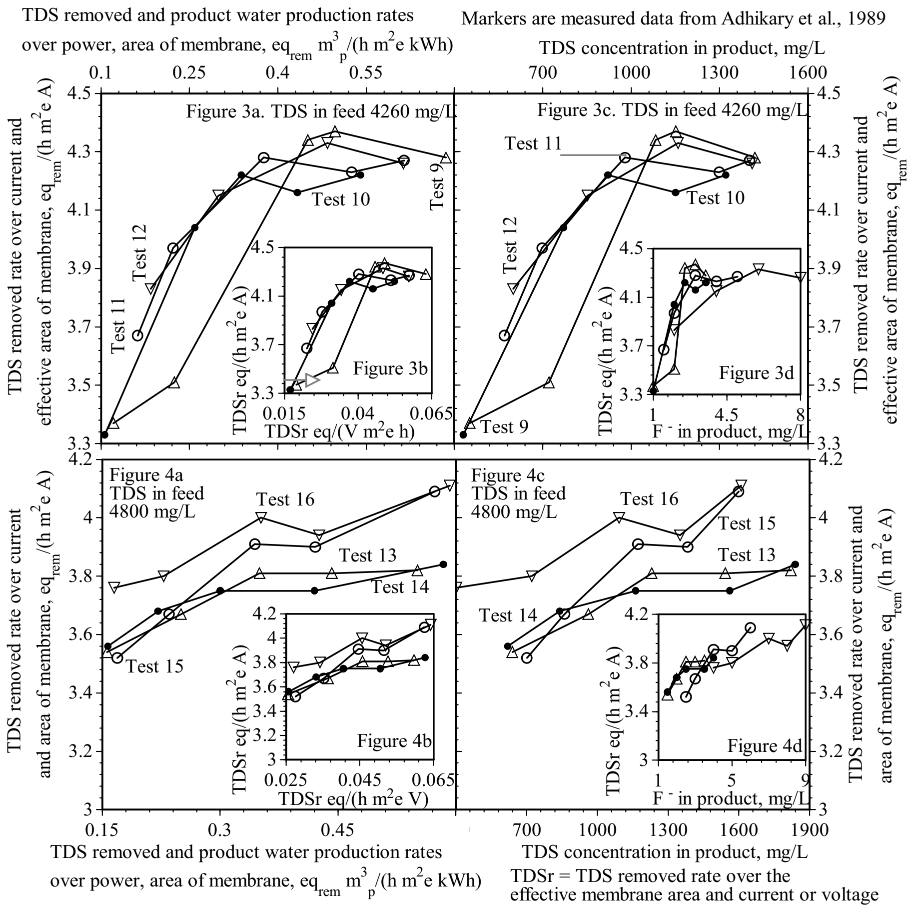


Fig. 3. Analyzed results for tests 9–12 with feed TDS concentration of 4260 mg/L.

Fig. 4. Analyzed results for tests 13–16 with feed TDS concentration of 4800 mg/L. (a) TDS removed and product water rates over the effective membrane area and power vs. TDS removed rate over the effective membrane area (EMA) and current. (b) TDS removed rate over the EMA and voltage vs. TDS removed rate over the EMA and current. (c) TDS concentration in product vs. TDS removed rate over the EMA and current. (d). F^- concentration in product vs. TDS removed rate over the EMA and current.

1–4, respectively. These read-out values are recorded in Columns 12, 13, and 14 of Table 2.

The average slope of curves in Figs. 1(a)–3(a) is the voltage required for one unit of product flow rate (volt/Q_p). The slope (voltage/Q_p) increases linearly at first, then slows down; it looks like, there is two different slopes. The higher the slope (volt/Q_p), the lesser value of the TDS removed (product water produced) rate over the effective area of membrane and current (power), so a lesser TDS concentration remained in product stream (Figs. 1(d)–3(d)). These behaviors are the same in the three different of feed water 2120, 3020, and 4260 mg/L in both Figs. 1 and 2.

The average slope of curves in Figs. 1(b)–3(b) is the total resistance (voltage divided by current; $R = V/A$) which is the total resistance of the membrane cell pair in stack. The slope (total resistance) increases linearly at first, then slows down. The more the slope (total resistance), the lesser TDS removed rate over the effective area of membrane and current (voltage) so a lesser TDS concentration remained in the product stream (Figs. 1(d)–3(d)). These behaviors are the same in three different feed waters 2120, 3020, and 4260 mg/L in both Figs. 1–3.

However, in Fig. 4(a), both of the slopes for voltage/Q_p and the total resistance for the feed water TDS 4800 mg/L only has one slope and the slope does not decrease. From this difference, one can conclude the higher the TDS concentration in the feed water, the higher the TDS removed (product water produced) rate over the effective area of member and current (power) in Figs. 4(a)–(c).

3.2 Equal flow rate in dilute and concentrate streams

Experiment test numbers 17–52 were operated with equal flow rate between dilute and concentrate streams. Experimental data for test numbers 17–32 were shown in [11] and summarized in Fig. 5 and Table 3. In Fig. 5, each figure contains a, b, and c of three types of sub-figures. TDS removed and volume of product water produced rates over the effective area of membrane and current are shown in figure type a. The relationship between TDS removed rate over the effective area of membrane and voltage against TDS removed rate over the effective area of membrane and current are depicted in figure type b. Figure type c shows the TDS concentration in the product against TDS removed rate over the effective area of membrane and current. Fig. 5 shows two different TDS concentrations in the feed of 3330 (solid line) and 7190 mg/L (dash line), respectively. Fig. 5 also depicts eight different product flow rates per the effective area of membrane (30.7, 44.3, 58, 71.6, 85.2, 98.9, 112.5, 126.1 L/h m^{2}e) respectively.

By using the corresponding value of TDS concentration in product from the Fig. 5(c), the corresponding values of TDS removed rate over the effective area of membrane and current were read from the TDS concentrations in the product stream. The corrected value of TDS removed rate over the effective area of membrane and current is used to determine the TDS removed (and volume of product water produced) rate over the effective area of membrane and voltage (power) from Fig. 5(b) (Fig. 5(a)), respectively. These read-out values are recorded in Columns 13, 14, and 15 of Table 3.

Experiment data from test numbers 33 to 45 and 46 to 52 were referred from [6,9] (Table 1). The average TDS concentrations in product are fixed as 320 mg/L with the lowest and highest values of 190 and 416 mg/L depending on data availability for the test numbers 33 to 52 in Table 3; the exact values used in the tests are shown in Column 12 of Table 3.

4. Monograph I – unequal flow rate in dilute and concentrate streams

The read-out data (TDS removed (volume of product water produced)) rate over the effective area of

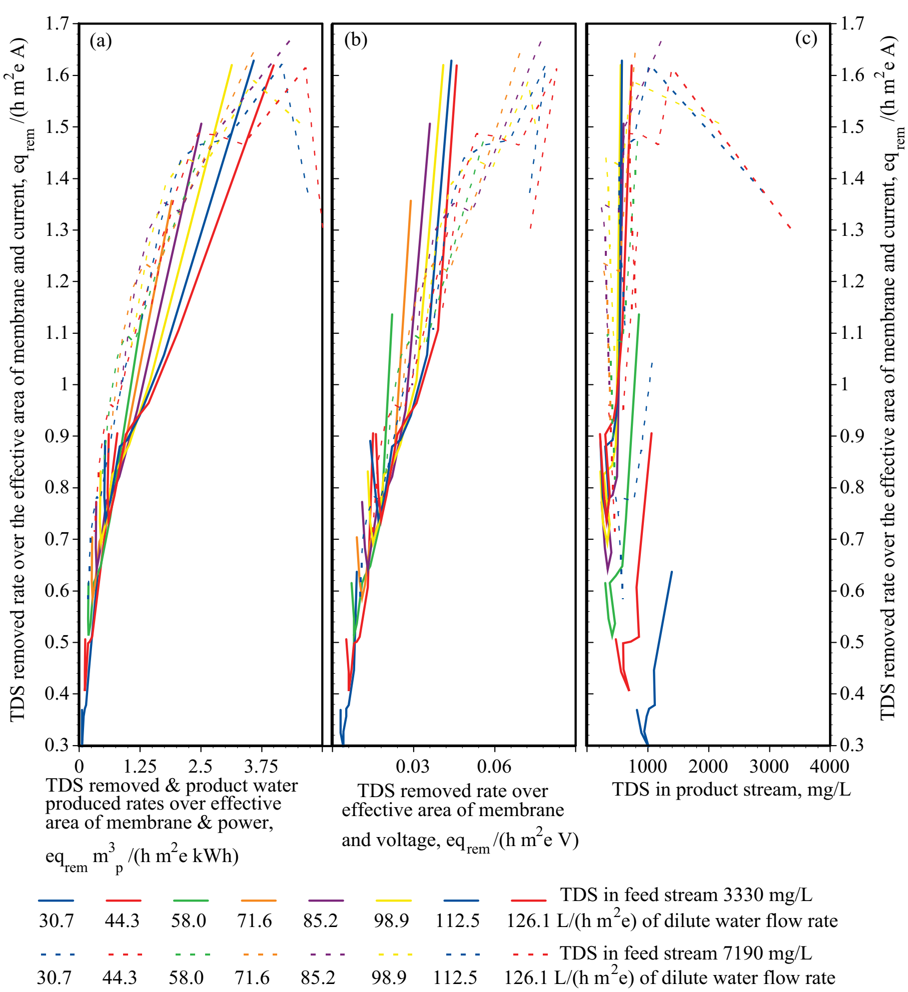
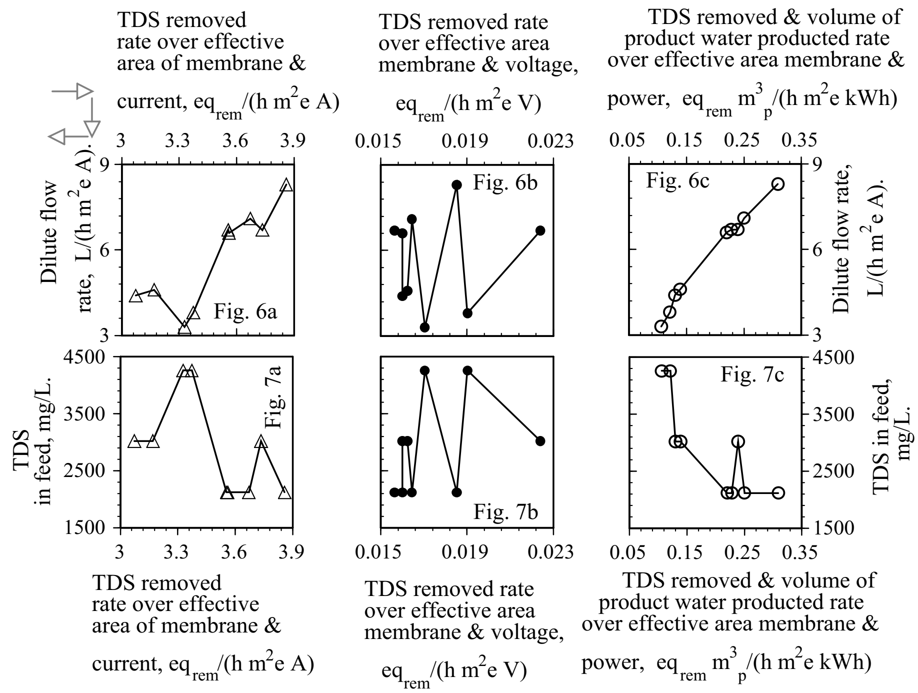


Fig. 5. Analyzed results of tests from 25 to 32 with the different dilute flow rate per the effective area of membrane.

Table 3
Resulting design parameters for ED/EDR: equal flow rates in dilute and concentrate steams

Test	Flow per effective area of membrane L/(h m²e)	Characteristics of water								Feed water	Product water	Design parameters		
		% ions concentration in feed water												
		WRR (%)	Na^+ (%)	K^+ (%)	Ca^{2+} (%)	Mg^{2+} (%)	Cl^- (%)	HCO_3^- (%)	SO_4^{2-} (%)	TDS (mg/L)	TDS (mg/L)	eq_{rem}/(h m²e A)	eq_{rem}/(h m²e V)	$eq_{rem}\ m^3_p$/(h m²e kWh)
19	58.0	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	3330	318	0.596	0.0075	0.190
20	71.6	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	3330	320	0.702	0.0141	0.421
21	85.2	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	3330	318	0.655	0.0128	0.358
22	98.9	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	3330	318	0.700	0.0151	0.451
23	112.5	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	3330	318	0.746	0.0172	0.547
24	126.1	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	3330	330	0.914	0.0157	0.615
26	44.3	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	7190	340	0.962	0.0231	0.417
27	58.0	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	7190	340	1.098	0.0302	0.622
28	71.6	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	7190	330	1.186	0.0320	0.711
29	85.2	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	7190	318	1.199	0.0339	0.761
30	98.9	50.0	39.3	0.0	0.0	0.0	60.7	0.0	0.0	7190	320	1.441	0.0517	1.393
36	89.6	86.6	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4141	416	0.088	0.0040	0.746
38	89.9	79.4	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4130	396	0.101	0.0040	0.870
34	92.2	78.3	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4190	395	0.102	0.0044	0.932
37	92.4	72.9	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4010	350	0.107	0.0040	0.925
35	93.4	82.8	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4015	405	0.094	0.0041	0.848
33	94.6	74.3	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4060	357	0.103	0.0044	0.971
39	94.6	84.3	32.5	0.1	3.7	1.0	51.2	1.6	9.9	3965	337	0.094	0.0042	0.867
43	91.0	86.8	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4023	365	0.098	0.0044	0.928
41	92.4	79.4	32.5	0.1	3.7	1.0	51.2	1.6	9.9	3955	341	0.105	0.0046	1.048
40	92.8	73.4	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4011	363	0.112	0.0046	1.121
42	92.8	84.0	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4069	385	0.102	0.0047	1.035
44	93.8	73.0	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4173	354	0.114	0.0050	1.174
45	97.0	83.7	32.5	0.1	3.7	1.0	51.2	1.6	9.9	4056	330	0.102	0.0051	1.111
50	93.1	86.1	12.2	0.0	13.6	4.3	24.1	12.9	32.8	1848	219	0.107	0.0020	1.097
52	93.1	90.0	15.0	0.0	12.0	3.7	27.7	12.9	27.3	1699	217	0.093	0.0017	0.927
51	94.1	88.8	12.7	0.0	13.5	4.1	26.4	12.1	31.1	1812	234	0.097	0.0021	1.082
47	95.2	76.7	14.0	0.0	12.3	3.9	25.3	15.8	28.6	1693	234	0.116	0.0018	1.201
46	95.9	73.0	14.6	0.0	12.4	3.9	27.7	12.7	28.7	1712	252	0.109	0.0020	1.301
48	96.6	83.4	11.9	0.0	14.0	3.9	23.4	12.8	34.0	1806	223	0.101	0.0023	1.268
49	96.6	86.0	12.7	0.0	13.7	4.0	23.8	12.8	33.0	1754	190	0.100	0.0021	1.145
53	78.2	84.2	13.5	0.0	9.0	4.2	2.1	30.9	40.2	1773	500	NA	NA	1.120

c = calculated.
WRR = water recovery rate
eq_{rem}/(h m²e A) = TDS removed rate over the effective area of membrane and current where eq represents equivalent weight of ions (TDS), and e represents effective.
eq_{rem}/(h m²e V) = TDS removed rate over the effective area of membrane and voltage where eq represents equivalent weight of ions (TDS), and e represents effective.
$eq_{rem}\ m^3_p$/(h m²e kWh) = TDS removed and product water produced rates over the effective area of membrane and power.
where, eq represents equivalent weight of ions (TDS), and e represents effective. p represents product water.

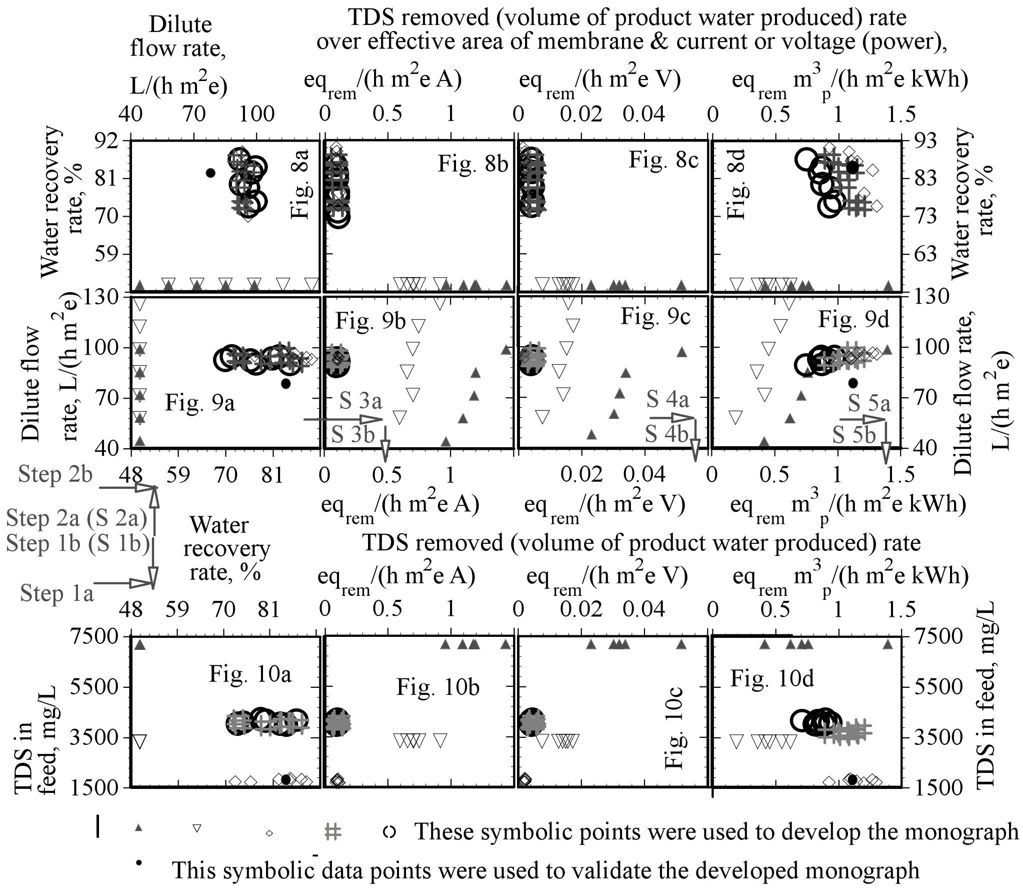


Monograph I (Figures 6–7). ED/EDR with unequal flow rate (flow rate ratio in dilute and concentrate = 3/1): TDS removed (volume of product water produced) rate over the effective area of membrane and current or voltage (power) against dilute flow rate over the effective area of membrane in Figure 6; and feed TDS concentration in Figure 7.

membrane and current or voltage (or power) which were recorded in Columns 12, 13, and 14 of Table 2 for test numbers 1–10, were grouped as a monograph I by combing Figs. 6 and 7. In Figs. 6 and 7, each figure contains three types of sub-figures a, b, and c. Fig. 6(a) shows the relation between TDS removed rate over the effective area of membrane and current against dilute flow rate per the effective area of membrane. Fig. 6(b) shows the relation between TDS removed rate over the effective area of membrane and voltage against dilute flow rate per effective area of membrane. Fig. 6(c) shows the relation between TDS removed and volume of product water produced rates over the effective area of membrane and power against dilute flow rate over the effective area of membrane. Fig. 7(a) shows the relation between TDS removed rate over the effective area of membrane and current against TDS concentration in the feed. Fig. 7(b) shows the relation between TDS removed rate over the effective area of membrane and voltage against TDS concentration in feed. Figure 7c shows the relation between TDS removed and volume of product produced rates over the effective area of membrane and power against TDS concentration in feed. From monograph I, the amount of TDS removed (and volume of product water produced) rate over the effective area of membrane and current or voltage (power) can be read with the respective dilute flow rate per effective membrane area and TDS concentrations in feed respectively.

5. Monograph II – equal flow rate in dilute and concentrate streams

The read-out data (TDS removed (volume of product water produced)) rate over the effective area of membrane and current or voltage (or power) which are recorded in Columns 13, 14, and 15 of Table 3, for test numbers 17–52 are grouped in a monograph II by combing Figs. 8–10. In Figs. 8–10, each figure contains four types of sub-figures (a), (b), (c), and (d). Fig. 8(a) shows the relation between dilute flow rates per effective area of membrane against water recovery rates (WRRs). Fig. 8(b) shows the relation between TDS removed rate over the effective area of membrane and current against WRRs. Fig. 8(c) shows the relation between TDS removed rate over the effective area of membrane and voltage against WRRs. Fig. 8(d) shows the relation between TDS removed and volume of product water produced rates over the effective area of membrane and power against WRRs. Fig. 9(a) shows the relation between WRRs against dilute flow rates per effective area of membrane. Fig. 9(b) shows the relation between TDS removed rate over the effective area of membrane and current against dilute flow



Monograph II (Figures 8–10). EDR with the equal flow: TDS removed (volume of product water) rate over the effective area of membrane and current or voltage (power) against the water recover rate in Figure 8; dilute flow rate over the effective area of membrane in Figure 9; and feed TDS concentration in Figure 10.

rate per effective area of membrane. Fig. 9(c) shows the relation between TDS removed rate over the effective area of membrane and voltage against dilute flow rate per effective area of membrane. Fig. 9(d) shows the relation between TDS removed and volume of product water produced rates over the effective area of membrane and power against dilute flow rate per effective area of membrane. Fig. 10(a) shows the relation between WRRs against TDS concentrations in feed stream. Fig. 10(b) shows the relation between TDS removed rate over the effective area of membrane and current against TDS concentrations in the feed stream. Figure 10c shows the relation between TDS removed rate over the effective area of membrane and voltage against TDS concentrations in the feed stream. Fig. 11(d) shows the relation between TDS removed and volume of product produced rates over the effective area of membrane and power against TDS concentrations in the feed stream. From monograph II, the amount of TDS removed (and volume of product water produced) rate over the effective area of membrane and current or voltage (power) can be read with the respective WRRs, dilute flow rate per effective membrane area, and TDS concentrations in the feed stream respectively.

The studies reveal that the quantities of these parameter are in the range of: 3–4.2 $eq_{rem}/(h\ m^2e\ A)$; 0.015–0.023 $eq_{rem}/(h\ m^2e\ V)$ and 0.1–0.35 eq_{rem} and $m^3_p/(h\ m^2e\ kWh)$ for EDR which operated with a ratio of 3 (flow rate in dilute/flow rate in concentrate), 3–9 $L/(h\ m^2e)$ of dilute flow rate per unit area of membrane and 2120–4260 mg/L of TDS in feed in Figs. 6 and 7. The range of these values are found to be 0–1.5 $eq_{rem}/(h\ m^2e\ A)$; 0–0.06 $eq_{rem}/(h\ m^2e\ V)$ and 0.1–1.4 eq_{rem} and $m^3_p/(h\ m^2e\ kWh)$ for EDR which operated with the equal flow rates in both dilute and concentrate streams with 30–130 $L/(h\ m^2e)$ of dilute flow rate per unit area of membrane, 1700–7190 mg/L of

TDS in the feed of dilute stream, and 53–93% of WRRs in Figs. 8–10.

6. Validating of the developed value of parameter 3 in equal flow rates of EDR

The developed value 0.1–1.4 eq_{rem} m^3_p/(h m^2e kWh) was validated with another set of lab data from the literature (1.151 eq_{rem} m^3_p/(h m^2e kWh) in 84.2% WRR and 78.2 L/(h m^2e) from [17]. The validated data point is in the range of developed value of parameter. The validation was also plotted in Figs. 8(a), 8(d), 9(a), 9(d), 10(a), and 10(d) in monograph II.

7. Physical meaning of parameters

The first-parameter, unit in eq_{rem}/h m^2e A, is defined as the mass of TDS removed rate over one unit of time (h), one unit square meter of effective area of membrane, and one unit of current (A). The second-parameter, unit in eq_{rem}/h m^2e V, is defined as the mass of TDS removed rate over one unit of time (h), one unit square meter of effective area of membrane, and one unit of voltage (V). The third-parameter, unit in eq_{rem} m^3_p/h m^2e kWh, is defined as the mass of TDS removed and volume of water product produced rates over one unit of time (h), one unit square meter of effective area of membrane, and one unit of power-hour (kWh).

All three parameters contain output per input. Output in the first- and second- parameters are mass of TDS removed (eq_{rem}); for the third parameter is mass of TDS removed plus volume of product clean water produced (eq_{rem} m^3_p). Input in the first-, second-, and third-parameters are processing time (h); effective area of membrane (m^2e); and current, voltage, time–power, respectively. The higher values of each parameter means the higher achievement in TDS removed (and volume of water product produced) rate from one units of time, effective area of membrane, and power input. The ratio of first parameter to second parameter (V/A) is defined as resistance of the process. Table 3 shows the higher ions concentration in feed water (7190 vs. 3330 mg/L NaCl) generates less process resistance (35 vs. 51 ohms) in the same conditions (water recovery rate 50%, dilute flow rate per unit effective area of membrane 85.2 L/(h m^2e), ions concentration of product water 318 mg/L). This finding harmonizes with Adhikary et al.'s [8] statement in which 1.15 V/cell pair is required to supply for water with TDS in feed water 0–24,170 mg/L while less voltage (1 V/cell pair) for feed water with TDS 27,100–36,000 mg/L due to the less total resistance occurs the higher TDS (ions) carrying feed water.

8. Trend in monograph I

Figs. 6(a) and (c) of monograph I show the values of TDS removed (and product water produced) rate over the effective area of membrane and current (power) increase with the increasing dilute flow rate per effective area of membrane; however, these values decrease with the increasing TDS in feed water (Fig. 7(a) and (c)). The reason for the increases of TDS removed (and product water produced) rate over the effective area of membrane and current (power) with the increasing dilute flow rate per effective area of membrane is the turbulence increases within the cell pair; the turbulence reduces the scale fouling on the surface of membranes.

9. Trend in Monograph II

The monograph II shows all the values of three design parameters explain the increasing trends with the increasing of dilute flow rate per unit effective area of membrane (Figs. 9(b)–(d)) at the same water recovery rate (50% in Fig. 8(a)) and the same feed TDS in dilute stream (3330 or 7190 mg/L in Fig. 10(a)). These increases may due to the turbulence.

The monograph II also reveals both the decreasing and increasing trends of TDS removed and product water produced rates over the effective area of membrane and power in Fig. 8(d) in the two different conditions of WRRs and flow rates of dilute stream. The decreasing trends of TDS removed and product water produced rates over the effective area of membrane and power in Fig. 8(d) with the increasing water recovery rates (73.0–86.8% in Fig. 8(a)) in the same dilute flow rate (91–97 L/(h m^2e)) in Fig. 9(a)) and in the same of TDS of feed water (3965–4190 mg/L in Fig. 10(a)). This finding is verified by another set of literature data (Fig. 8(d)) with the same TDS of feed water 1693–1848 mg/L (Table 3; Fig. 10(a)) in the increasing water recovery rates from 73% to 90% (Table 3; Fig. 8(a)). The decreasing trends of TDS removed and product water produced rates over the effective area of membrane and power in Fig. 8(d) with the increasing water recovery rates (Fig. 8(d)) is due to the increasing ion concentration in the concentrate stream of EDR when water recovery rate is increased beyond a certain limit which tends to decrease the demineralization rate and diminish current efficiency. Fig. 8(d) also reveals the increasing trend of TDS removed and product water produced rates over the effective area of membrane and power at the constant water recovery rate (50%) but with the increasing dilute flow rate (Fig. 9(d)). This increasing trend of TDS removed and product water produced rates over the effective area of membrane and power at the constant water recovery rate (50%) but with the increasing dilute flow rate (Fig. 9(d)) is due to the higher velocity and turbulent in the surface of membrane to provide the lower fouling at the surface of membrane and to increase the level of the limiting current density.

10. The usefulness of parameters

The developed three parameters can be used to predesign the EDR by using the developed monographs. For example, monograph I is for unequal (flow rate ratio in dilute and concentrate stream = 3) dilute flow of EDR; monograph II for equal flow rate of EDR. In equal flow rate of EDR, for a given of TDS 3330 mg/L feed water, TDS 318–330 mg/L in product water, 50% water recovery rate, the TDS removed (and product water produced) rate over the effective area of membrane and current or voltage (power) can be read from Figs 9(b)–(d) from the dilute flow rate per unit effective area of membrane.

Step 1: identify the correct symbolic icon from Fig. 10(a) for the desired level of TDS concentration in feed of dilute stream and WRRs. For example, for a 3330 mg/L of TDS concentration in feed of dilute stream and 50% of WRRs, the correct symbolic icon is empty triangle. Step 2: identify the correct symbolic icon (e.g., empty triangle) from Fig. 8(a) and/or 9(a) for the desired dilute flow rate (e.g., 71.6 L/(h m^2e) with the known information of WRRs 50%. Step 3: by using the identified symbolic icon and the known information, the TDS removed (and product water produced) rate over the effective area of membrane and current or voltage (power) can be read from Fig. 9(b), (c), and (d), respectively. From Figs. 9(b)–(d), the read-out values are 0.695 eq_{rem}/(A m^2e h), 0.0139 eq_{rem}/(V m^2e h), and 0.417 eq_{rem} m^3_p/(kWh m^2e h) for 71.6 L/(h m^2e) of dilute flow rate per unit effective area of membrane and feed TDS 3330 mg/L.

11. Identifying the optimal flow rate per effective area of membrane

The purpose of ED/EDR desalination is to gain a consistent highest yield of TDS removed (and product water produced) rate over a given power and the effective area of membrane over the whole design life-time of ED/EDR. This developed pre-design parameter can be used to pin-point the optimal operation condition (i.e., dilute flow rate per effective area of membrane) in the same of feed water, the same of WRRs, the similar TDS in the product stream. For example, from Table 3, the optimal flow rate per effective area of membrane for the tests 40–45 is 93.8 L/(h m^2e) which generates the highest TDS removed (product water produced) rate over the effective area of membrane and power. This value decreases although the dilute flow rate per effective area of membrane increases from 93.8 to 97 L/(h m^2e). Similarly, the optimal dilute flow rate per unit effective area of membrane for the tests 46–49 is 95.9 L/(h m^2e) in Table 3 for another set of feed water and operation condition.

12. Conclusion

Three comprehensive design parameters are developed and proposed as TDS removed rate over the effective area of membrane and current, eq_{rem}/(A m^2e h); TDS removed rate over the effective area of membrane and voltage, eq_{rem}/(V m^2e h); TDS removed and product water rates over the effective area of membrane and power, eq_{rem} m^3_p/(kWh m^2e h). The quantity of the parameters is found to vary with the TDS concentration in feed of dilute stream, ions composition in feed water, ion loading rate, dilute flow rate over effective area of membrane, and the water recovery rate.

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